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A High-Resolution Gamma-Ray Geophysical Survey for the Evaluation of Radiogenic Heat in Tiouit, Morocco's Eastern Anti-Atlas: Prospects for Sustainable Energy.

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Abstract

The application of radiogenic heat production (RHP) data, obtained from high-resolution gamma-ray spectrometric measurements, can offer significant information in the context of geothermal and clean energy resource exploration. In the Tiouit region, located in the Eastern Anti-Atlas, Morocco, gamma-ray spectrometric data were used to calculate the contribution of heat production elements U, Th, and K, and their distribution in the area, in relation to different geological formations. Based on the international classification criteria, most of the geological formations in the area present moderate levels of radiogenic heat production, varying from 1.38 to 1.96 μW/m³. Higher RHP values of approximately 2.10 μW/m³ are related to the rhyolite ignimbrite formations and rhyolite-rich conglomerates. This suggests these geological formations are of significant interest for the exploration of the geothermal resources of the region. While the granodiorite formation has moderate RHP value levels of approximately 1.79 μW/m³, the extensive geographical area covered by the formation makes it a significant contributor to the RHP of the region. The mafic and pelitic formations have moderate RHP value levels.

I. Introduction

Quantification of radiogenic heat production (RHP) requires the quantification of the concentration of radioactive isotopes through various methods like gamma-ray spectrometry, laboratory chemical analysis, and in situ measurements. Rybach (1976) and Pollack et al. (1993) have formulated empirical formulas to estimate the RHP in the form of microwatts per cubic meter based on the concentration of elements. High-resolution airborne gamma-ray spectrometry allows the mapping of RHP variations over large areas. Such measurements of RHP have been conducted for various areas across the globe (Ikechukwu et al., 2025, Youssef, 2016). RHP data represents the geological history and the composition of the crust of the area of interest.

Radiogenic heat production influences various geological activities like metamorphism, magmatism, and mineralization. Areas of high RHP represent higher geothermal gradients and tectonic activity. Integration of RHP data with other geophysical data improves the model of the Earth's crust's thermal evolution. Such regional investigations provide essential information for the exploration of geothermal energy resources. RHP information improves the understanding of the geological setting of the area of interest. This research aims to investigate the RHP of the area of interest, i.e., the Tiouit area, through high-resolution airborne gamma-ray spectrometry. The methodology of the research involves the quantification of the concentration of uranium, thorium, and potassium. This information is then used to estimate the RHP. The research aims to investigate the RHP of the area of interest and to identify the areas of high RHP. This information is then correlated with the geological setting of the area. Integration of geophysical information improves the overall understanding of the RHP of the area.

II. Presentation of the study area

The study area is in the Eastern Anti-Atlas region in Morocco, in the northern part of the West African Craton. The Anti-Atlas Belt is a major Precambrian inlier, characterized by a complex geological history from the Neoproterozoic to the Paleozoic eras, as described by Michard (1976). In particular, the Tiouit district is genetically linked with the Jbel Saghro massif, which is one of the major Neoproterozoic domains in southern Morocco, formed during the Pan-African orogenic event, as described by Gasquet et al. (2008) and Beakhouse and Davis (2005). The massif experienced significant magmatic and tectonic activity, including arc formation, thickening of the crust, and late-orogenic extension, all of which are associated with the Pan-African orogen, as described by Ben-Tami et al. (2024) and Beakhouse and Davis (2005). These rocks include calc-alkaline and alkaline granitoids, rhyolitic and andesitic volcanic rocks, and associated volcano-sedimentary sequences, all of which are cut by major shear zones and faults that controlled the emplacement of magma and hydrothermal activity.

The Tiouit region has already been identified as a potentially significant area in terms of its metallogeny, including its gold mineralization associated with Pan-African structures and felsic intrusions, as described by Beakhouse and Davis (2005). This demonstrates the close link between the emplacement of granitoids and mineralization, which indicates the strong interrelationship between magmatism, tectonics, and hydrothermalism in the region.

The radiogenic content of rocks in the study area, specifically the felsic plutonic and volcanic rocks in the Jbel Saghro massif, indicates significant levels of uranium, thorium, and potassium, all of which are a consequence of differentiation and reworking of the crust, as described by Rybach (1976). These elements are primarily present in the form of accessory minerals, K-feldspar, and mica in the granitoids, while in the case of mafic rocks, they are present in significantly smaller amounts due to their mantle origin.

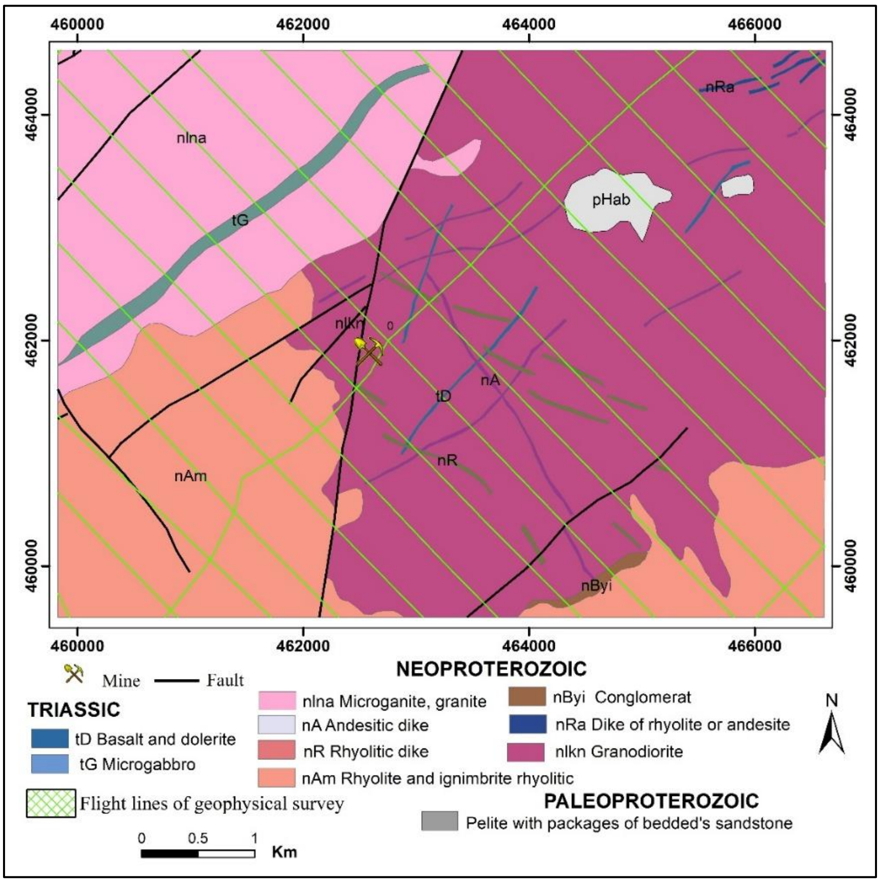

Fig. 1: A geological map of the study area with the gamma-ray spectrometry geophysical survey on top (Hawkins et al., 2001).

III. Methods

1. Gamma-ray spectrometry data

Radiogenic heat production (RHP) was carried out using high resolution airborne gamma ray spectrometry data from the Tiouit region in the Eastern Anti-Atlas, Morocco. The data was provided by the Ministry of Energy, Mines and Sustainable Development of Morocco.

The flight lines were flown with an average flight altitude of 60 meters. The main flight lines flow in a NW to SE direction with a flight line spacing 500 m. The tie lines are flown in a NE to SW direction with a flight line spacing 4000 m (Fig. 1).

Radiometric measurements were carried out by a multi-channel Exploranium GR-820 gamma ray spectrometer with downward-looking NaI(Tl) crystals (16.8 L total volume) and upward-looking crystals (4.2 L total volume) to assist with atmospheric and background correction. The spectrometer detects five main energy windows:

- Total Count: 0.42–3.00 MeV
- Potassium (K): 1.373–1.574 MeV
- Uranium (U): 1.660–1.860 MeV
- Thorium (Th): 2.414–2.816 MeV
- Cosmic background: 3.00–6.00 MeV

The positioning and navigation were achieved through an Ashtech GLONASS GS24 GPS receiver with differential correction. The PAL color video system was also incorporated to facilitate ground control.

The radiometric data was processed in accordance with standard correction protocols used in airborne gamma-ray spectrometry surveys, as recommended by various authors (Li et al., 2021; IAEA, 2003; Grasty et al., 1997). The corrections included cosmic radiation correction and elimination of background radiation from the aircraft. Altitude correction was used to normalize the data to a constant height, considering the clearance over the terrain and the exponential decay of gamma rays in the atmosphere, as described in IAEA (2003).

The Radon background correction used the upward-looking detector to account for atmospheric Radon and its progenies. The Compton stripping correction ensured minimal overlap between potassium, uranium, and thorium spectral windows to ensure a precise separation between these elements. The lag correction ensured compensation for the offset between detector response and aircraft position resulting from response time.

The corrections ensure that the final concentrations of K (%), U (ppm), and Th (ppm) are a true representation of ground radioelement concentrations and form a solid foundation upon which radiogenic heat production calculations are based.

2. Radiogenic Heat Production Calculation

Radiogenic heat production (RHP) was calculated using the concentrations of potassium (K, %), uranium (U, ppm), and thorium (Th, ppm) according to the following equation (Sanjurjo-Sánchez et al., 2022):

$$\mathrm{RHP}\left(\frac{\mu\mathrm{W}}{\mathrm{m}^3}\right) = 10^{-5} * \rho * (9.52 * \mathrm{C_U} + 2.56 * \mathrm{C_{Th}} + 3.48 * \mathrm{C_K})$$

where:
ϱ = rock density (g/cm³). 2.7 g/cm³.An average crustal density was used for the calculation.

C_U, C_{Th}, C_K= concentrations of the elements.

3. Geological Integration and Spatial Analysis

The integration of the radiometric results was performed using the geological map of the area studied. In this way, the spatial variability of the RHP was analyzed. In the process, lithologies were classified according to the international standards for RHP (Turcotte & Schubert, 2014; Rybach, 1976):

- Low heat production (<1 µW/m³)
- Moderate heat production (1-2 µW/m³)
- High heat production (>2 µW/m³)

4. Statistical Analysis and Interpretation

Descriptive statistics were applied to the results to analyze the intra- and inter-lithological variability in the RHP. In the process, the results were correlated to the lithologies, their mineralogical composition, and the structural features controlling the former gold mining area of Tiouit. Special emphasis was given to the felsic lithologies, which are rich in U, Th, and K and are known to significantly contribute to the heat production in the Earth's crust.

IV. Results and discussion

The statistical analysis of radiogenic heat production in the study area indicates a wide variation in both space and lithology, reflecting the complex geological history of the Eastern Anti-Atlas region. The mean radiogenic heat production varies from 1.39 to 2.14 µW/m³. This indicates that all lithologies fall within the moderate to locally high radiogenic heat production category. None of these lithologies fall within the low radiogenic heat production category (< 1 µW/m³), suggesting that this study area belongs to a relatively radiogenically enriched upper crustal domain (Fig.2).

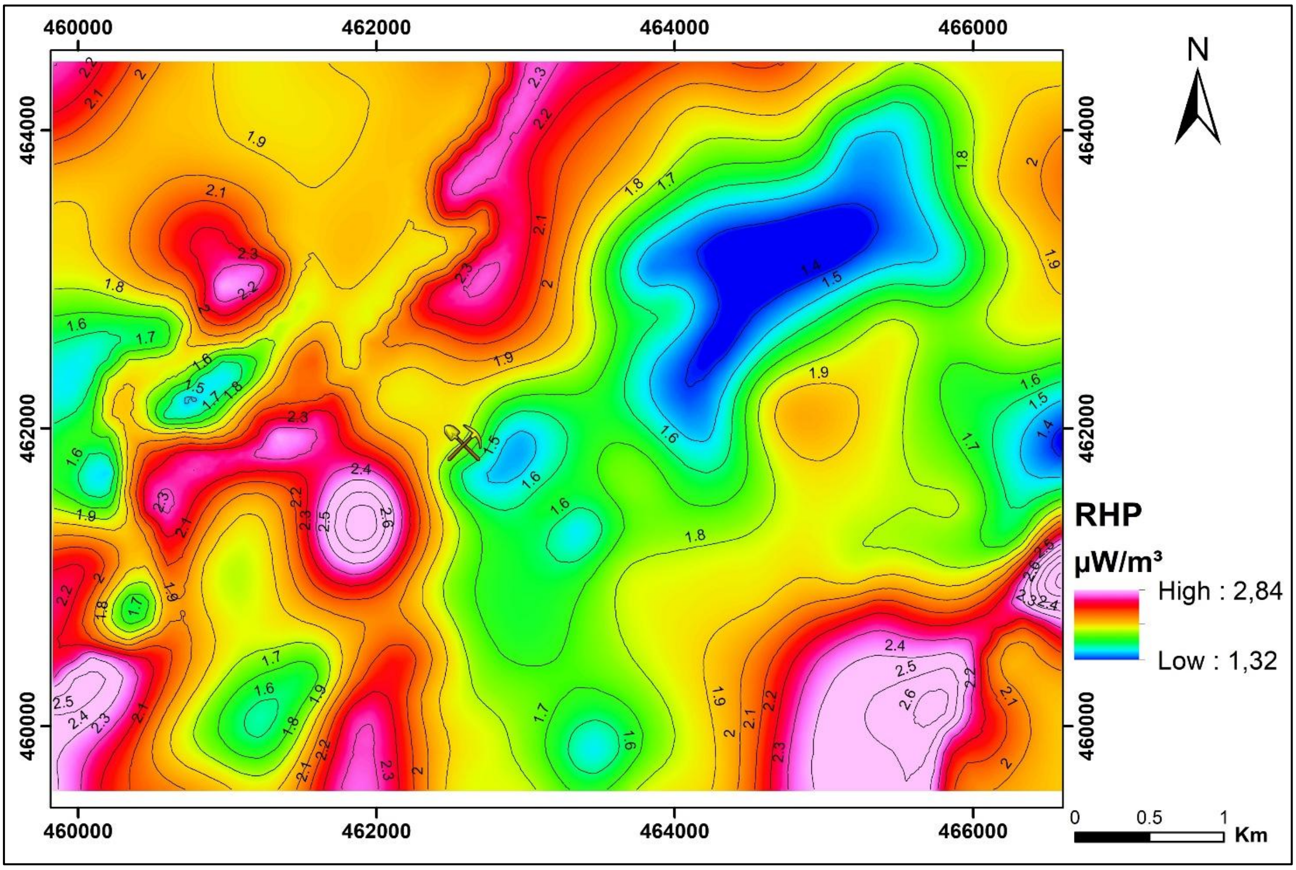

Fig. 2: Spatial distribution of Radiogenic Heat Production in the study area based on airborne geophysical data.

The highest mean values of radiogenic heat production are found in Neoproterozoic lithologies, particularly in nByi (2.14 µW/m³) and in nAm (2.10 µW/m³). The high values in these lithologies suggest felsic magmatic rocks with high concentrations of Uranium and Thorium, indicating high magmatic differentiation. The highest value in the lithology nAm is 2.84 µW/m³, suggesting a zone of enrichment in this lithology, possibly resulting from magmatic fractionation or hydrothermal alteration resulting from Pan-African tectono-magmatic events.

The majority have moderate values of radiogenic heat production, ranging from 1.66 to 1.96 µW/m³, including Triassic and some Neoproterozoic formations. The Paleoproterozoic unit (pHab) has the lowest mean value of radiogenic heat production at 1.39 µW/m³, suggesting a less evolved or mafic composition. This is consistent with global trends in crustal radiogenic heat production, in which felsic compositions have higher values than mafic ones.

The dispersion parameters provide further interesting information on internal heterogeneity. The standard deviations vary from 0.08 to 0.23 µW/m³, and the coefficient of variation (CV) ranges from 4.61 to 12.17%. For instance, the nIkn and nAm units present higher CVs, i.e., higher than 10%, which could indicate heterogeneity in composition, structural complexity, and possible mineralogical zonation in these units. On the other hand, the units with lower CVs indicate homogeneous radiogenic distributions (Table 1).

The present study has shown that, despite some units presenting higher RHP, the spatial distribution and volume of radiogenic rocks play a significant role in regional radiogenic heat production, as opposed to the commonly used concept of heat intensity, where a higher RHP value indicates a higher contribution to regional heat production. For instance, the nIkn unit presents a moderate RHP value of 1.79 µW/m³, but its large surface area, i.e., 18.59 km², makes it the dominant contributor to the total radiogenic heat production, whereas other units present higher RHP but smaller surface areas (Table 1).

Table 1: Radiogenic heat production $\left(\frac{\mu W}{m^3}\right)$ statistics for lithological units in the Tiouit area.

ID	Index	Age	Area (km^2)	Min	Max	Range	Mean	SD	CV (%)	Sum
1	tD	Triassic	0.10	1.41	2.04	0.63	1.66	0.17	10.37	413.47
2	tG		0.47	1.66	2.32	0.66	1.96	0.15	7.55	2384.52
3	nlna	Neoproterozoic	6.88	1.49	2.39	0.89	1.95	0.18	9.08	33180.15
4	nA		0.27	1.37	2.21	0.84	1.76	0.19	10.57	1244.96
5	nR		0.14	1.52	2.38	0.87	1.77	0.16	8.94	644.10
6	nAm		8.12	1.51	2.84	1.33	2.10	0.23	11.12	43999.24
7	nByi		0.09	1.84	2.43	0.59	2.14	0.18	8.57	516.51
8	nRa		0.06	1.61	1.89	0.29	1.82	0.08	4.61	209.07
9	nlkn		18.59	1.35	2.83	1.48	1.79	0.22	12.17	83216.89
10	pHab	Paleoproterozoic	0.43	1.33	1.71	0.38	1.39	0.08	5.72	1569.72

In a geological context, the Neoproterozoic sequence dominating both magnitude and area in radiogenic heat production indicates a high degree of influence from felsic magmatism in the Pan-African orogeny. The high concentrations of uranium, thorium, and potassium in granitoids and rhyolite formations are a result of crustal differentiation and reworking typical in felsic magmatic settings. The link between felsic magmatism and established gold deposits also suggests a contribution from hydrothermal systems to radiogenic enrichment.

The study indicates a high degree of influence from lithology and magmatic evolution in radiogenic heat production in the Tiouit district. The Neoproterozoic felsic sequence is identified as a major source in radiogenic heat production, with extensive and moderately productive lithologies being a key contributor to regional radiogenic heat production. The study provides a solid foundation for geothermal assessment in the Eastern Anti-Atlas region, highlighting the need to integrate radiometric data with geological mapping in a quest to harness this form of sustainable energy.

V. Conclusion

This research has successfully demonstrated the mapping of radiogenic heat production in the Tiouit area. The research has provided valuable information regarding radiogenic heat production of the area. The Neoproterozoic felsic units have been demonstrated to have the highest potential for radiogenic heat production. These units have the highest radiogenic heat production and the largest area. Thus, these units have the highest potential for the exploration of geothermal resources. Moreover, the moderate radiogenic heat production of the large area of lithologies has demonstrated the importance of the exploration of the entire area. This research has provided a strong basis for the exploration of radiogenic heat production. This research has demonstrated the potential of the Eastern Anti-Atlas for the exploration of radiogenic heat production. This research has provided valuable information for the exploration of the entire sector of the Eastern Anti-Atlas.

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